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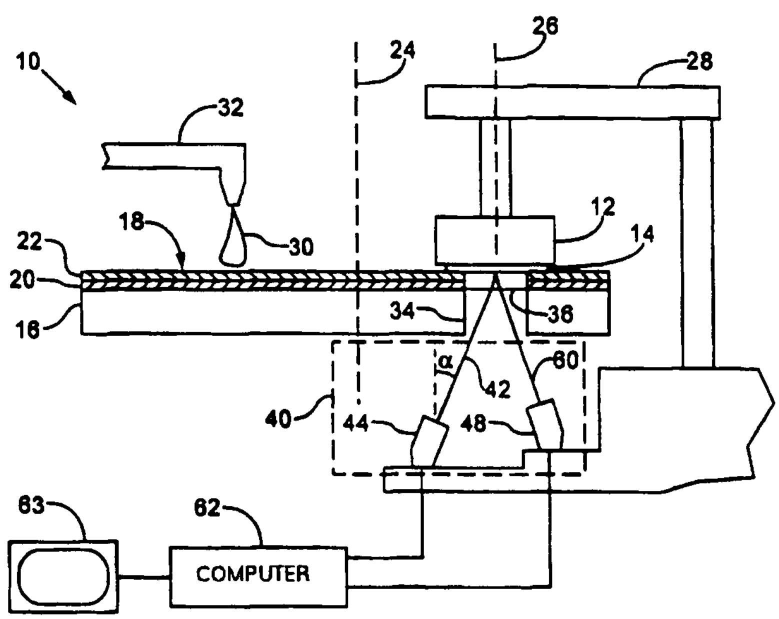

(57) **Abstract**

A predicted in–situ reflectivity measurement (ISRM) trace is calculated for a substrate undergoing a chemical mechanical polishing. This predicted ISRM trace is an estimate of the measured reflectivity of the substrate as a function of time. During polishing, a laser interferometric detector is used to measure the reflectivity of the substrate and generate a measured ISRM trace. The measured trace is compared to the predicted trace, and the polishing process may be adjusted based on the comparison. For example, the predicted ISRM trace may be used to detect the polishing endpoint.

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METHOD AND APPARATUS FOR MODELING SUBSTRATE REFLECTIVITY DURING CHEMICAL MECHANICAL POLISHING

BACKGROUND

The present invention relates generally to chemical mechanical polishing of substrates, and more particularly to monitoring the reflectivity of substrates in a chemical mechanical polishing apparatus.

An integrated circuit is typically formed on a substrate by the sequential deposition of conductive, semiconductive or insulative layers on a silicon wafer. After each layer is deposited, the layer is etched to create circuitry features. As a series of layers are sequentially deposited and etched, the outer or uppermost surface of the substrate, i.e., the exposed surface of the substrate, becomes increasingly non-planar. This non-planar surface presents problems in the photolithographic steps of the integrated circuit fabrication process. Therefore, there is a need to periodically planarize the substrate surface.

Chemical mechanical polishing (CMP) is one accepted method of planarization. This planarization method typically requires that the substrate be mounted on a carrier or polishing head. The exposed surface of the substrate is placed against a rotating polishing pad. The polishing pad may be either a "standard" pad or a fixed-abrasive pad. A standard pad has a durable roughened surface, whereas a fixed-abrasive pad has abrasive particles held in a containment media. The carrier head provides a controllable load, i.e., pressure, on the substrate to push it against the polishing pad. A polishing slurry, including at least one chemically-reactive agent, and abrasive particles if a standard pad is used, is supplied to the

surface of the polishing pad.

One problem in CMP is determining whether the polishing process is complete, i.e., whether a substrate layer has been planarized to a desired flatness or thickness. Thus, there is a need to detect the polishing endpoint.

Variations in the polishing conditions can impede an accurate determination of the polishing endpoint. For example, variations in the slurry composition, the polishing pad condition, the relative speed between the polishing pad and the substrate, and the load of the substrate on the polishing pad can cause variations in the material removal rate. These variations cause variations in the time needed to reach the polishing endpoint. Therefore, the polishing endpoint cannot be determined merely as a function of polishing time.

One approach to determining the polishing endpoint is to remove the substrate from the polishing surface and examine it. If the substrate does not meet the desired specifications, it is reloaded into the CMP apparatus for further processing. Alternatively, the examination might reveal that an excess amount of material has been removed, rendering the substrate unusable. There is, therefore, a need for a method of detecting, in-situ, when the desired flatness or thickness had been achieved.

Several methods have been developed for in-situ polishing endpoint detection. Most of these methods involve monitoring a parameter associated with the substrate surface, and indicating an endpoint when the parameter abruptly changes. For example, where an insulative or dielectric layer is being polished to expose an underlying metal layer, the coefficient of friction and the

reflectivity of the substrate will change abruptly when the metal layer is exposed.

In an ideal system where the monitored parameter changes abruptly at the polishing endpoint, such endpoint detection methods are acceptable. However, as the substrate is being polished, the polishing pad condition and the slurry composition at the pad-substrate interface may change. Such changes may mask the exposure of an underlying layer, or they may imitate an endpoint condition. Additionally, such endpoint detection methods will not work if only planarization is being performed, if the underlying layer is to be over-polished, or if the underlying layer and the overlying layer have similar physical properties.

An additional problem is characterization of the endpoint criteria. If the monitored parameter is to be compared to a preselected value which represents the polishing endpoint, the preselected value must be determined before the polishing operation is initiated. Typically, the endpoint criteria are determined by measuring the parameter associated with a substrate known to have the desired layer flatness or thickness. However, because the endpoint criteria are not yet known, a test substrate must be processed using the previously described technique of periodically removing the substrate from the CMP apparatus, examining it, and reloading it into the CMP apparatus if it does not meet the desired specifications. Once the desired specifications are met, the parameter value monitored at the point when the polishing ceased is used as the endpoint criteria. Thus, determining the endpoint criteria is a time consuming and labor intensive procedure.

In view of the foregoing, there is a need for a polishing endpoint detector which accurately and reliably

determines when to stop the polishing process. There is also a need for a method of quickly and reliably characterizing the endpoint criteria.

SUMMARY

In one aspect, the invention is directed to a method of predicting the reflectivity of a substrate as measured in-situ during a polishing operation. The substrate includes a layer disposed on a wafer. The method comprises constructing a model of the substrate, the model including an initial thickness and a refractive index for the layer, estimating a thickness of the layer as a function of time, and determining a reflectivity of the substrate as a function of time from the estimated thickness and the refractive index of the layer.

Implementations of the invention may include the following. The reflectivity of the substrate may also determined from a refractive index of the wafer, a refractive index of an entry medium, and an angle of incidence of a light beam used to measure the reflectivity. The reflectivity of the substrate may be determined by generating a first matrix for a first region of the substrate, and generating a second matrix for a second region of the substrate. A first reflectivity may be determined from the first matrix, a second reflectivity may be determined from the second matrix, and the first and second reflectivities may be averaged. A characteristic matrix may be generated for each layer in the first and second regions, and the characteristic matrixes for the layers in the respective regions may be multiplied to generate the first and second matrixes. The thickness may be estimated by iteratively estimating a current polishing

rate and adjusting a current thickness based on the current polishing rate. Estimating the thickness may include estimating a polishing rate and adjusting a current thickness based on the current polishing rate. Estimating the current polishing rate may include modifying a base polishing rate by a factor which depends upon a height difference between two regions of the substrate.

In another aspect, the invention is directed to a method of performing a chemical mechanical polishing process. A time-varying reflectivity of a substrate undergoing a polishing operation is predicted, a time-varying reflectivity of the substrate is measured in-situ during a polishing operation, the predicted reflectivity is compared to the measured reflectivity, and the process is adjusted based on the comparison.

Implementations of the invention may include the following. The polishing process may be halted when the measured reflectivity reaches a preselected portion of the predicted reflectivity. The predicted reflectivity may be revised based on the measured reflectivity. Predicting the reflectivity may include constructing a model of the substrate. The model may including an initial thickness and a refractive index for the layer. A thickness of the layer may be estimated as a function of time, and a predicted reflectivity of the substrate may be determined as a function of time from the estimated thickness and the refractive index of the layer.

In another aspect, the invention is directed to a chemical mechanical polishing apparatus for polishing a substrate including a layer disposed on a wafer. The apparatus comprises a platen to support a polishing pad, a polishing head to hold the substrate against the polishing

pad during processing, a light source to generate a light beam which impinges on a surface of the substrate, and a sensor to measure light reflected from the surface of the substrate and generate a measured reflectivity signal. A computer is configured to store a model of the substrate, the model including an initial thickness and a refractive index for the layer, to estimate a thickness of the layer as a function of time, and to determine a predicted reflectivity signal as a function of time from the estimated thickness and the refractive index of the layer.

Implementations of the invention may include the following. The processor may be configured to compare the measured reflectivity signal to the predicted reflectivity signal, and the apparatus may further comprise an output device for displaying the predicted reflectivity signal. The light source and sensor may be part of a laser interferometer.

Advantages of the invention include the following. A predicted in-situ reflectance measurement trace may be calculated. This permits endpoint criteria to be characterized without polishing of a test substrate. The predicted trace may be compared to a measured trace to accurately predict and detect the polishing endpoint.

Other features and advantages of the invention will become apparent from the following description, including the drawings and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a side view of a chemical mechanical polishing apparatus including an optical interferometer in accordance with the present invention.

FIG. 2 is a simplified cross-sectional view of a

substrate being processed, schematically showing a laser beam impinging on and reflecting from the substrate.

FIG. 3 is a flow chart of a method of determining the endpoint of a CMP process.

FIGS. 4A-4E are simplified cross-sectional views of a patterned substrate at different stages of a CMP process.

FIG. 5 is a flow chart of a method of predicting an in situ reflectivity measurement (ISRM) trace.

FIG. 6 is a graph showing a predicted ISRM trace.

FIG. 7 is a flow chart of a method of data acquisition from an optical interferometer.

DESCRIPTION OF THE PREFERRED EMBODIMENT(S)

Referring to FIG. 1, a CMP apparatus 10 includes a polishing head 12 for holding a substrate 14 against a polishing pad 18. The polishing pad 18 is supported by a platen 16. The polishing pad typically has a backing layer 20 which abuts the surface of platen 16 and a covering layer 22 which is used to polish substrate 14. Covering layer 22 is typically harder than backing layer 20. However, some pads have only a covering layer and no backing layer. Covering layer 22 may be composed of an open cell foamed polyurethane or a sheet of polyurethane with a grooved surface. Backing layer 20 may be composed of compressed felt fibers leached with urethane. A two-layer polishing pad, with the covering layer composed of IC-1000 and the backing layer composed of SUBA-4, is available from Rodel, Inc., of Newark, Delaware (IC-1000 and SUBA-4 are product names of Rodel, Inc.).

The platen is rotated about its central axis 24. In addition, the polishing head is rotated about its central axis 26 and translated across the surface of the polishing

pad by a translation arm 28. Although just one polishing head is shown in FIG. 1, CMP apparatus 10 may include more than one of these polishing heads. A description of a multi-head CMP apparatus may be found in U.S. Patent Application Serial No. 08/549,336, entitled RADIALLY OSCILLATING CAROUSEL PROCESSING SYSTEM FOR CHEMICAL MECHANICAL POLISHING, by Ilya Perlov, et al., filed October 27, 1995 and assigned to the assignee of the present invention, the entire disclosure of which is incorporated herein by reference.

A slurry 30 containing a reactive agent (e.g., deionized water for oxide polishing) and a chemically-reactive catalyzer (e.g., potassium hydroxide for oxide polishing) may be supplied to the surface of polishing pad 18 by a slurry supply port 32. If polishing pad 18 is a standard pad, slurry 30 may also include abrasive particles (e.g., silicon dioxide for oxide polishing). Sufficient slurry is provided to cover and wet the entire polishing pad.

A hole 34 is formed in platen 16 and a transparent window 36 is formed in a portion of polishing pad 18 overlying the hole. Transparent window 36 may be constructed as described in U.S. Patent Application Serial No. 08/689,930, entitled METHOD OF FORMING A TRANSPARENT WINDOW IN A POLISHING PAD FOR A CHEMICAL MECHANICAL POLISHING APPARATUS by Manoocher Birang, et al., filed August 26, 1996, and assigned to the assignee of the present invention, the entire disclosure of which is incorporated herein by reference. Hole 34 and transparent window 36 are positioned such that they have a view of substrate 14 during a portion of the platen's rotation, regardless of the translational position of the polishing head. A laser

interferometer 40 is located below platen 16. The laser interferometer includes a laser 44 and a detector 48. The laser generates a collimated laser beam 42 which propagates through transparent window 36 and slurry 30 (see FIG. 2) to impinge upon the exposed surface of substrate 14. The laser beam 42 is projected from laser 44 at an angle α from an axis normal to the surface of substrate 14, i.e., at an angle α from axes 24 and 26.

Laser 44 is activated to generate laser beam 42 during a time when hole 34 is adjacent substrate 14. In operation, CMP apparatus 10 uses laser interferometer 40 to determine the amount of material removed from the surface of the substrate, or to determine when the surface has become planarized. A general purpose programmable digital computer 62 may be connected to laser 44 and detector 48. Computer 62 may be programmed to predict the reflectivity of the substrate as a function of time, to activate the laser when the substrate overlies the window, to store measurements from the detector, to display the measurements on an output device 63, and to detect the polishing endpoint.

Referring to FIG. 2, substrate 14 includes a silicon wafer 50 and an overlying structure 52. The portion of laser beam 42 which impinges on substrate 14 will be partially reflected at the surface of structure 52 to form a first reflected beam 54. However, a portion of the laser beam will also be transmitted through structure 52 to form a transmitted beam 56 which impinges on the underlying wafer 50. At least some of the light reaching wafer 50 from transmitted beam 56 will be reflected back through structure 52 to form a second reflected beam 58. The first and second reflected beams 54, 58 interfere with each other constructively or destructively depending on their phase

relationship, to form a resultant beam 60. The phase relationship of the reflected beams is primarily a function of the index of refraction and thickness of the layers in structure 52, the wavelength of laser beam 42, and the angle of incidence of the laser beam.

Although structure 52 could be just a single layer, this interference process is generally applicable to multiple layer structures. If each layer is partially reflective and partially transmissive, a resultant interference beam will be created, although it will be a combination of the reflected beams from all the layers and the wafer.

The resultant beam 60 propagates back through slurry 30 and transparent window 36 to detector 48. If the reflected beams 54, 58 are in phase with each other, they cause a maxima on the detector. On the other hand, if the reflected beams are out of phase, they cause a minima on the detector. Other phase relationships will result in an interference signal between the maxima and minima being seen by the detector. The result is a signal output from detector 48 that varies with the thickness of the layer or layers in structure 52.

Because the thicknesses of the layers in structure 52 change with time as the substrate is polished, the signal output from detector 48 also varies with time. The time varying output of detector 48 may be referred to as an in-situ reflectance measurement (ISRM) trace. This ISRM trace may be used for a variety of purposes, including selecting an endpoint, characterizing the CMP process, and sensing that the CMP apparatus is not operating properly.

Referring to FIG. 3, CMP apparatus 10 may perform an endpoint detection method 70. First, a predicted ISRM trace

is calculated (step 72). This predicted ISRM trace is an estimate of the reflectivity of substrate 14 measured by detector 48 as a function of time. In brief, the predicted ISRM trace is generated using an optical model which includes a thickness and a refractive index for each of the layers disposed on the wafer. A point on the predicted ISRM trace which corresponds to the desired thickness or planarity of substrate 14 is marked (step 73). Then, during polishing, laser interferometer 40 is used to measure the reflectivity of substrate 14 and generate a measured ISRM trace (step 74). The measured trace is compared to the predicted trace (step 75). When the measured trace reaches the marked point on the predicated trace (step 76) polishing operations are halted (step 78). Each of the steps of this endpoint detection method will be discussed in further detail below.

For the sake of clarity, the calculation of the predicated ISRM trace will be discussed for a particular polishing operation on a particular type of substrate. Specifically, an ISRM trace will be calculated for the removal of a silicon oxide layer which overlies a patterned nitride layer. The usual purpose of such a polishing operation is to planarize the silicon oxide layer until the underlying patterned nitride layer is exposed.

Referring to FIG. 4A, substrate 14 includes silicon wafer 50 and structure 52 deposited thereon. Structure 52 includes an active area 80 (which need not be a contiguous region) and an isolation area 82 (which also need not be a contiguous region). The active area 80 includes a silicon layer 84, a layer of epitaxially grown silicon oxide 85, and a silicon nitride layer 86. The portions of wafer 50 which are not coated with layers 84-86 constitute isolation area

82. During fabrication, the entire substrate, including both active area 80 and isolation area 82, is coated with a silicon oxide layer 88. Because the silicon oxide layer 88 is deposited over a patterned active area 80, an outer surface 90 of the silicon oxide layer is non-planar. Specifically, the portions of silicon oxide layer 88 in active area 80 project above the portions of silicon oxide layer 88 in isolation area 82 to form trenches 92. Prior to polishing, the height difference or "step height" between the active area and the isolation area may be up to about 2.0 microns. Typically, the active area is higher than the isolation area, but some fabrication processes, such as etching, may be used prior to polishing to generate a slightly negative step height.

Silicon layer 84 has a typical initial thickness D_1 of about 0.1 to 1.0 microns, epitaxial silicon oxide layer 85 has a typical initial thickness D_2 of approximately 100 to 500 angstroms, and silicon nitride layer 86 has a typical initial thickness D_3 of about 0.1 to 1.0 microns. Prior to polishing, silicon oxide layer 88 has a total thickness D_4 in active area 80 and a total thickness D_5 in isolation area 82. Thickness D_4 and D_5 will be about the same because they are deposited by the same process, although thickness D_4 may be slightly less than thickness D_5. Thickness D_5 will be sufficient for a bottom surface 98 of trench 92 to be above silicon nitride layer 86.

Referring to FIG. 4B, at the beginning of the polishing operation, polishing pad 18 may contact only the portions of silicon oxide layer 88 in active area 80. Polishing pad 18 is shown only in FIGS. 4B and 4C for the purpose of clarity. Because covering layer 22 has some compressibility, a portion 64 of covering layer 22 will

project into trench 92. Referring to FIG. 4C, eventually the portions of silicon oxide layer 88 in active area 80 will be polished away until they are sufficiently thin that portion 64 of covering layer 22 will contact bottom surface 98 of trench 92. At this point, the portions of silicon oxide layer 88 in both isolation area 82 and active area 80 will be polished. Since the polishing pad is more compressed over active area 80, the force applied to surface 96 will be greater than the force applied to surface 98, and the polishing rate will be higher in active area 80 than in isolation area 82. However, because the chemically reactive agent and abrasive particles in the slurry can reach the bottom of trench 92, surface 98 may be polished even when it is not contacted by the polishing pad.

Referring to FIG. 4D, eventually silicon oxide layer 88 will be polished until silicon nitride layer 86 is exposed. Although polishing could cease at this point, substrate 14 is typically slightly over-polished to ensure that all of the active area is exposed. This may be necessary because some parts of the substrate, such as the center, might be polished more slowly than other parts of the substrate, such as the edge. Referring to FIG. 4E because silicon nitride layer 86 tends to polish more slowly than silicon oxide layer 88, the overpolishing tends to create a "dishing" effect which results in indentations 94 in the silicon oxide layer in isolation area 82.

Referring to FIG. 5, the process for calculating a predicted ISRM trace (step 72 in FIG. 3) for the substrate shown in FIGS. 4A-4E will be discussed in greater detail. First, the thicknesses of the layers in structure 52 are estimated as a function of time (step 100). Next, the reflectivities of the isolation area and the active area are

calculated (step 102). This includes calculating a characteristic matrix for each layer in the structure from the thickness and refractive index of the layer (step 104), multiplying the matrixes to generate a master matrix for each area (step 106), and calculating the reflectivities for each area from the master matrix (step 108). Finally, the average reflectivity of the substrate is determined from the reflectivities of the active and isolation areas (step 110). Because the thicknesses of the layers in structure 52 have been determined as a function of time, the average reflectivity of the substrate may also be predicted as a function of time. By plotting the predicted average reflectivity of the substrate as a function of time, the CMP apparatus may generate a predicted ISRM trace. Each of the above steps will be discussed in greater detail below.

To estimate the thickness of the various layers of the substrate, computer 62 is programmed to store the base thicknesses D_1, D_2, D_3, D_4 and D_5 of the layers in structure 52 and base polishing rates PR_{oxide} and $PR_{nitride}$ for silicon oxide layer 88 and silicon nitride layer 86, respectively. The polishing rates PR_{oxide} and $PR_{nitride}$ may be experimentally determined by test polishing "blank" substrates, i.e., wafers coated with an unpatterned layer of silicon oxide or silicon nitride. The thickness of each layer in structure 52 is calculated at a series of measurement times t_0, t_1, t_2, ...t_i, t_{i+1}, ...t_n. The measurement times may be separated by a standard time interval Δt of, for example, one second. Thus, in a polishing operation which takes approximately five minutes, 300 thickness calculations are performed for each layer in structure 52. The thicknesses of the layers may be iteratively calculated from the following equation:

$$d(t_i) = d(t_{i-1}) - PR(t_{i-1}) \cdot \Delta t$$

with the initial starting conditions:

$$d_1(t_0) = D_1 \quad d_2(t_0) = D_2 \quad d_3(t_0) = D_3 \quad d_4(t_0) = D_4 \quad d_5(t_0) = D_5$$

where d(t) is the thickness of the particular layer and PR(t) is the polishing rate of the layer. Of course, only the exposed layers are polished, and therefore PR(t) is set to zero for any layer that is unexposed. A reasonable estimate of the polishing rate for an exposed layer is a base polishing rate for that layer plus a conversion factor which is multiplied by the height difference between the active area and isolation area. Thus, the polishing rate PR(t) may be approximated for the oxide and nitride layers with the following equations:

$$PR_{oxide} = PR_{oxide} + \Gamma_{oxide} \cdot StepHeight$$

$$PR_{nitride} = PR_{nitride} - \Gamma_{nitride} \cdot StepHeight$$

where StepHeight is the height difference between the active area and the isolation area, i.e., $d_1 + d_2 + d_3 + d_4 - d_5$ (see FIG. 4B) and Γ is an experimentally determined constant. An appropriate value for Γ_{oxide} and $\Gamma_{nitride}$ is approximately 0.7. There may also be a maximum polishing rate PR_{max}. In addition, during the start of polishing operation, for example, during the first five to fifteen seconds, lower polishing rates may be used to simulate the initial

processing conditions.

Once the thicknesses of the layers have been determined in step 100, a characteristic matrix is calculated for each layer in active area 80 and isolation area 82. The characteristic matrix M for an arbitrary layer is given by the following equation:

$$M = \begin{bmatrix} \cos k_0 h & \dfrac{i \sin k_0 h}{\Upsilon} \\ \Upsilon i \sin k_0 h & \cos k_0 h \end{bmatrix}$$

where

$$h = 2nd \cdot \cos\theta \qquad k_0 = \frac{2\pi}{\lambda_0} \qquad \Upsilon = n \cdot \cos\theta$$

and λ_0 is the wavelength of laser beam 42, n is the index of refraction of the layer, d is the thickness of the layer, and θ is the angle of refraction of the light entering the layer. The angle of refraction θ may be calculated as follows:

$$\frac{\sin\theta}{\sin\alpha} = \frac{n_{air}}{n}$$

where α is the angle of between laser beam 42 and an axis normal to the substrate surface (see FIG. 1). After calculating the characteristic matrix for each layer, the matrixes are multiplied to generate a master matrix M_{active} for active area 80 and a master matrix $M_{isolation}$ for isolation area 82. Specifically, the master matrixes M_{active} and $M_{isolation}$ are given by the following equations:

$$M_{active} = M_{oxide} \cdot M_{nitride} \cdot M_{epi} = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix}$$

$$M_{isolation} = M_{oxide} = \begin{bmatrix} m_{11}' & m_{12}' \\ m_{21}' & m_{22}' \end{bmatrix}$$

Once the master matrixes have been calculated in step 106, reflectivities R_{active} and $R_{isolation}$ for active area 80 and isolation area 82, respectively, may be calculated from the following equations:

$$R_{active} = \left| \frac{\Upsilon_0 m_{11} + \Upsilon_0 \Upsilon_S m_{12} - m_{21} - \Upsilon_S m_{22}}{\Upsilon_0 m_{11} + \Upsilon_0 \Upsilon_S m_{12} + m_{21} + \Upsilon_S m_{22}} \right|^2$$

$$R_{isolation} = \left| \frac{\Upsilon_0 m_{11}' + \Upsilon_0 \Upsilon_S m_{12}' - m_{21}' - \Upsilon_S m_{22}'}{\Upsilon_0 m_{11}' + \Upsilon_0 \Upsilon_S m_{12}' + m_{21}' + \Upsilon_S m_{22}'} \right|^2$$

where

$$\Upsilon_0 = n_0 \cdot \cos\theta_0 \qquad \Upsilon_S = n_S \cdot \cos\theta_S$$

and n_0 is the index of refraction of the incident medium, θ_0 is the angle of incidence in the incident medium, n_S is the index of refraction of the final medium, and θ_S is the angle of refraction of the final medium. Referring to FIG. 2, the

incident medium is slurry 30 and the final medium is silicon wafer 50. Thus, θ_0 and θ_S may be calculated as follows:

$$\frac{\sin\theta_0}{\sin\alpha} = \frac{n_{air}}{n_{slurry}} \qquad \frac{\sin\theta_S}{\sin\alpha} = \frac{n_{air}}{n_{silicon}}$$

Once the reflectivities R_{active} and $R_{isolation}$ have been calculated in step 108, the average reflectivity of the substrate may be determined. Specifically, interference between the active area and the isolation area does not appear to contribute significantly to the reflectivity of the substrate. Consequently, the average reflectivity may be calculated as a simple average given by the equation below:

$$R_{average} = a \cdot R_{active} + (1 - a) \cdot R_{isolation}$$

where a is the percentage of the surface of substrate 14 that is covered by active area 80. The percentage of active area a is determined by the die design and may be obtained from the circuit designer.

Referring to FIG. 6, an ISRM trace is shown by line 115. As the thicknesses of the various layers change with time, the total reflectivity of the substrate also changes. The ISRM trace of FIG. 6 was calculated using the values from Tables 1 and 2 below:

Table 1

layer	initial thickness (angstroms)	refractive index (n)	base polishing rate (angstroms/ minute)
slurry	n/a	1.33 (n_0)	n/a
oxide in isolation area	7000 (D_5)	1.46	2100
oxide in active area	6800 (D_4)	1.46	2100
nitride	1800 (D_3)	2.01	700
epitaxial oxide	200 (D_2)	1.46	n/a
silicon layer	3400 (D_1)	4.0 (n_S)	n/a
silicon wafer	n/a	4.0 (n_S)	n/a

Table 2

isolation area (a)	0.5
incidence angle (α)	16°
wavelength (λ)	6700 Angstroms
polishing time	210 seconds
polishing interval (Δt)	1 second

Returning to FIG. 3, once the ISRM trace has been calculated in step 72, it may be displayed on output device 63 (see FIG. 1). Then, in step 73 the desired endpoint is determined by finding the time at which the desired planarity or layer thickness has been achieved. The total reflectivity at that point in time is marked. For example,

as shown in FIG. 6, a dot 117 may be placed in the predicted ISRM trace.

Once the predicted ISRM trace has been calculated and an endpoint selected, a substrate is polished and a measured ISRM trace is generated during the CMP process. The platen 16 will typically be rotating. Therefore, platen hole 34 will only have a view of substrate 14 during part of its rotation. Accordingly, the detection signal from laser interferometer 40 should only be sampled when substrate 14 is impinged by laser beam 42. It is important that the detection signal not be sampled when a portion of laser beam 42 is blocked, because this will cause considerable noise in the signal. A position sensor (not shown) may be used to generate a signal which is used to determine when the signal from detector 48 is to be sampled as described in the above-mentioned U.S. Serial No. 08/689,930.

The measured ISRM trace (step 74 in FIG. 3) may be obtained by integrating the signal from detector 48 over one or more revolutions of the platen. In reference to FIG. 7, the laser interferometer signal is sampled during the available data acquisition time in each rotation of the platen (step 122). Next, each sampled signal is integrated over the aforementioned data acquisition time, and the integrated values are stored (steps 124 and 126). Then, a cumulative sample time is computed after each complete revolution of the platen and compared to a desired minimum sample time (steps 128 and 130). Of course, this would constitute only one sample time if only one sample has been taken. If the cumulative sample time equals or exceeds the desired minimum sample time, then the stored integrated values are transferred and summed (step 132). If not, the process of sampling, integrating, storing, computing the

cumulative sample time, and comparing it to the desired minimum sample time continues. Finally the summed integrated values created each time the stored integrated values are transferred and summed, are output as the ISRM signal (step 134). The just-described data collection method can be implemented in a number of well known ways, employing either logic circuits or software algorithms.

As the ISRM trace is measured by steps set forth in FIG. 7, the measured reflectivity from the measured ISRM trace is compared to the predicted reflectivity from the predicted ISRM trace. If the predicted trace does not match the detected trace, the base polishing rates PR_{oxide} and $PR_{nitride}$ may be adjusted and the predicted ISRM trace may be recalculated. The base polishing rates may be manually adjusted by the operator based on a visual inspection of the predicted and measured ISRM traces. Alternatively, computer 62 may be programed to search for minima and maxima in the measured trace, compare these minima and maxima to the predicted minima and maxima from the predicted ISRM trace, and use this information to adjust the predicted polishing rates. If significant differences between the predicted trace and the measured trace remain, then it is likely that there is an error in the optical model. However, assuming that the detected trace substantially follows the predicted trace, then once the detected trace reaches the specified reflectivity, the polishing operation is halted.

In addition, operator may adjust the polishing process parameters, such as the rotational speed of the polishing head, the rotational speed of the platen, the polishing load, and the slurry composition and flow rate, based on a comparison of the predicted and measured ISRM traces. For example, if the operator notes that the

measured ISRM trace is lagging behind the predicted ISRM trace, the operator may increase the polishing load so as to increase the polishing rate. Alternately, the computer may be programmed to compare the measured ISRM trace to the predicted ISRM trace and adjust the process parameters.

The present invention has been described in terms of a preferred embodiment. The invention, however, is not limited to the embodiment depicted and described. Rather, the scope of the invention is defined by the appended claims.

What is claimed is:

1. A method of predicting the reflectivity of a substrate as measured in-situ during a polishing operation, the substrate including a layer disposed on a wafer, comprising:

constructing a model of the substrate, the model including an initial thickness and a refractive index for the layer;

estimating a thickness of the layer as a function of time; and

determining a reflectivity of the substrate as a function of time from the estimated thickness and the refractive index of the layer.

2. The method of claim 1, wherein the reflectivity of the substrate is also determined from a refractive index of the wafer, a refractive index of an entry medium, and an angle of incidence of a light beam used to measure the reflectivity.

3. The method of claim 1, wherein determining the reflectivity of the substrate includes generating a first matrix for a first region of the substrate, and generating a second matrix for a second region of the substrate.

4. The method of claim 3, wherein determining the reflectivity of the substrate includes determining a first reflectivity from the first matrix, determining a second reflectivity from the second matrix, and averaging the first and second reflectivities.

5. The method of claim 3, wherein generating the first and second matrixes includes generating a

characteristic matrix for each layer in the first region, generating a characteristic matrix for each layer in the second region, multiplying the characteristic matrixes for the layers in the first region to generate the first matrix, and multiplying the characteristic matrixes for the layers in the second region to generate the second matrix.

6. The method of claim 1, wherein estimating the thickness includes iteratively estimating a current polishing rate and adjusting a current thickness based on the current polishing rate.

7. The method of claim 1, wherein the substrate includes a first layer in a first region of the substrate and a second layer in a second region of the substrate, and wherein estimating the thickness includes estimating a first polishing rate for the first layer, estimating a second polishing rate for the second layer, adjusting a first current thickness of the first layer based on the first current polishing rate, and adjusting a second current thickness of the second layer based on the second current polishing rate.

8. The method of claim 7, wherein estimating the first current polishing rate includes modifying a first base polishing rate by a first factor which depends upon a height difference between the first and second regions of the substrate.

9. The method of claim 8, wherein estimating the second current polishing rate includes modifying a second base polishing rate by a second factor which depends upon

the height difference between the first and second regions of the substrate.

10. A method of performing a chemical mechanical polishing process, comprising:

predicting a time-varying reflectivity of a substrate undergoing a polishing operation;

measuring a time-varying reflectivity of the substrate in-situ during a polishing operation;

comparing the predicted reflectivity to the measured reflectivity; and

adjusting the process based on the comparison.

11. The method of claim 10, wherein adjusting the process comprises halting the polishing process when the measured reflectivity reaches a preselected portion of the predicted reflectivity.

12. The method of claim 10, further comprising revising the predicted reflectivity based on the measured reflectivity.

13. The method of claim 10, wherein the substrate has a layer disposed on a wafer, and wherein predicting the reflectivity includes constructing a model of the substrate, the model including an initial thickness and a refractive index of the layer, estimating a thickness of the layer as a function of time, and determining a predicted reflectivity of the substrate as a function of time from the estimated thickness and the refractive index of the layer.

14. A chemical mechanical polishing apparatus,

substrate, the model including

refractive index for the layer, to estimate a thickness for each of the layer as a function of time, and to determine a predicted reflectivity signal as a function of time from the estimated thickness and the refractive index of the layer.

15. The apparatus of claim 14, wherein the processor is further configured to compare the measured reflectivity signal to the predicted reflectivity signal.

16. The apparatus of claim 14, further comprising an output device for displaying the predicted reflectivity signal.

17. The apparatus of claim 14, wherein the light source and sensor are part of a laser interferometer.

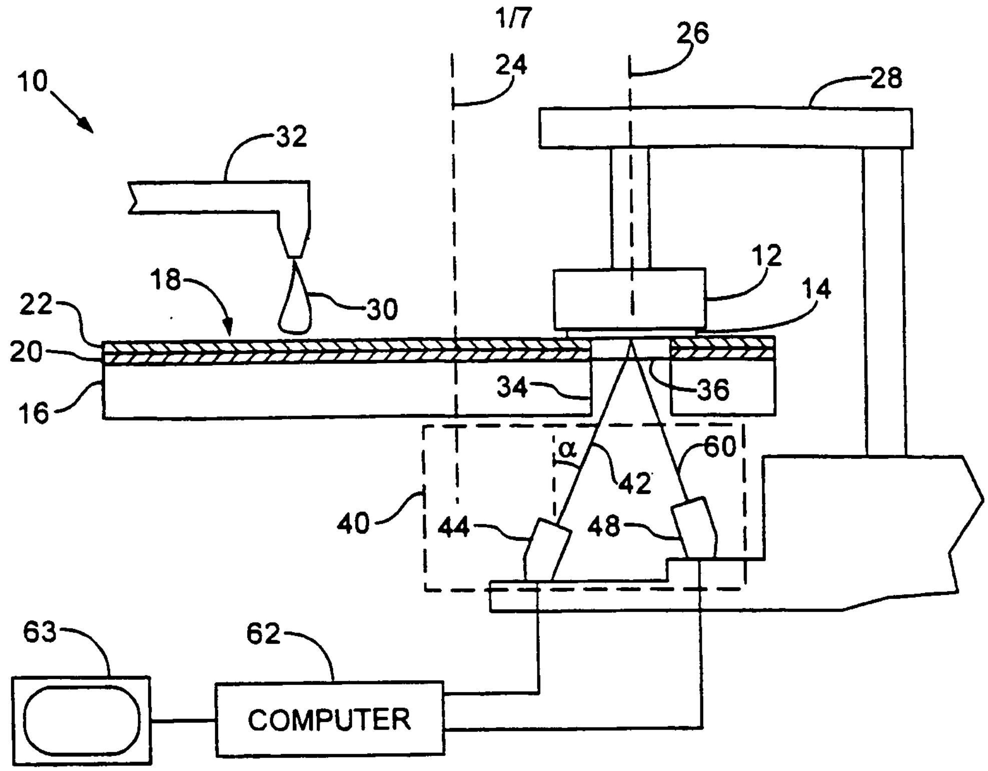
10
32
28
26
24
12
14
18
22
30
20
34
36
16
α
42
60
40
44
48
63
62
COMPUTER

FIG. 1

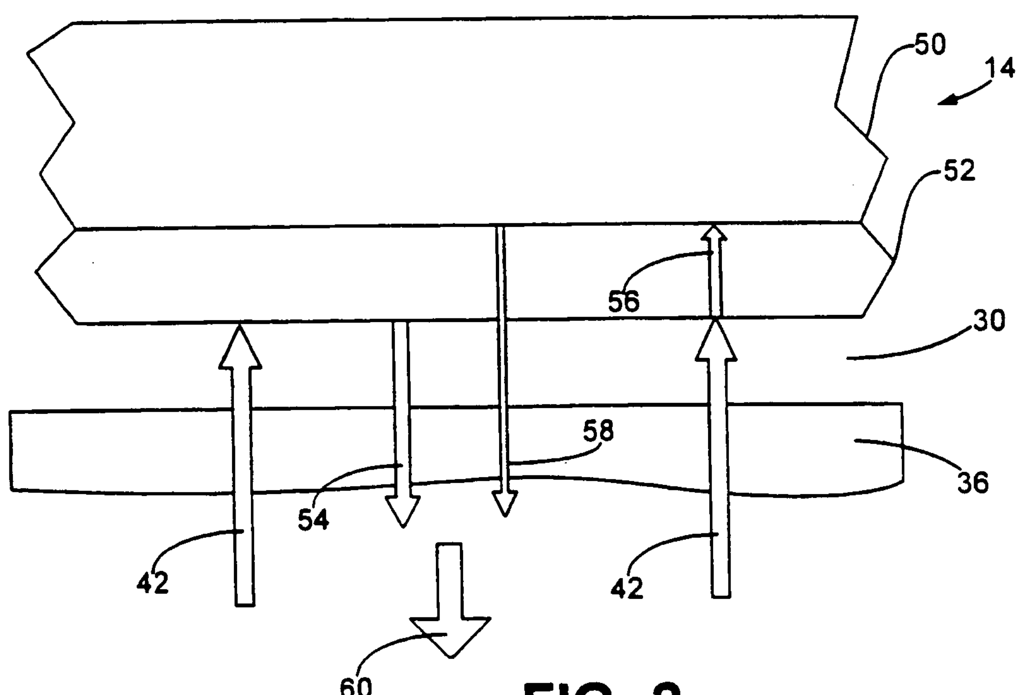
50
14
52
56
30
58
36
54
42
42
60

FIG. 2

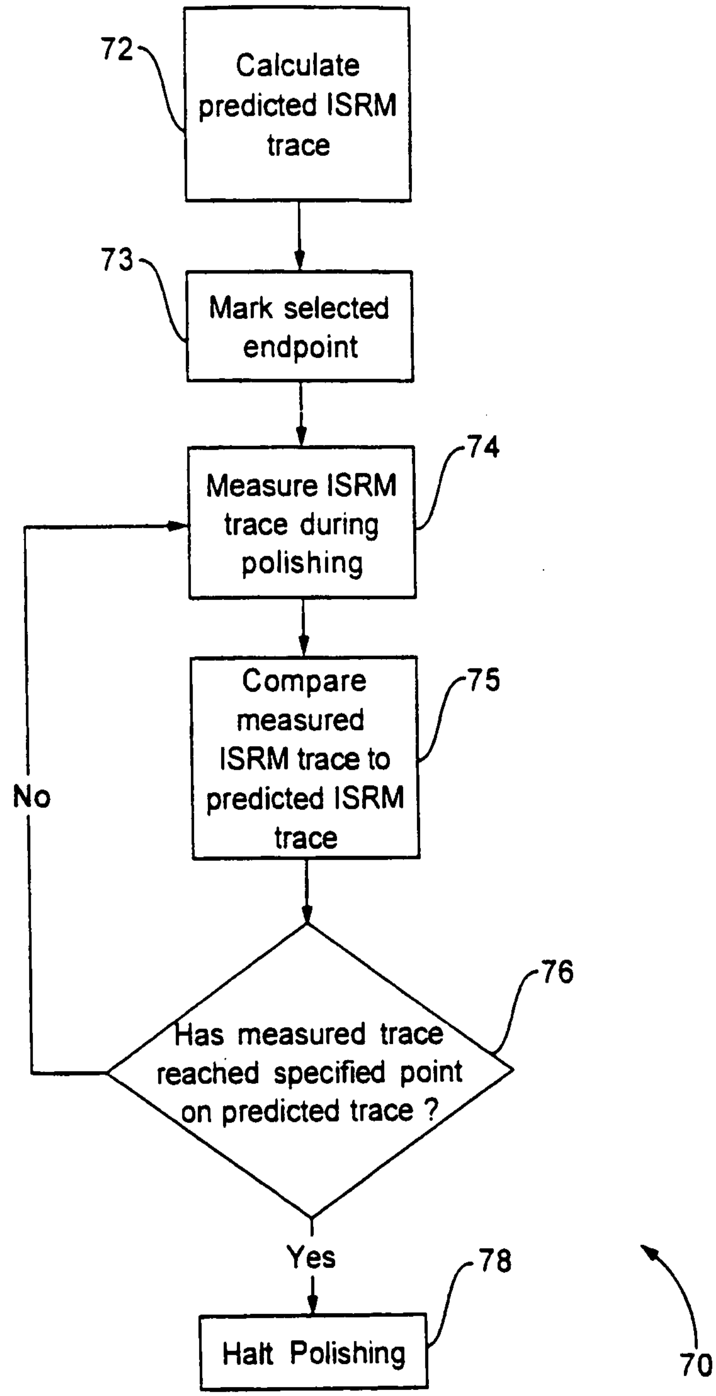
72
Calculate predicted ISRM trace
73
Mark selected endpoint
74
Measure ISRM trace during polishing
75
Compare measured ISRM trace to predicted ISRM trace
No
76
Has measured trace reached specified point on predicted trace ?
Yes
78
Halt Polishing
70

FIG. 3

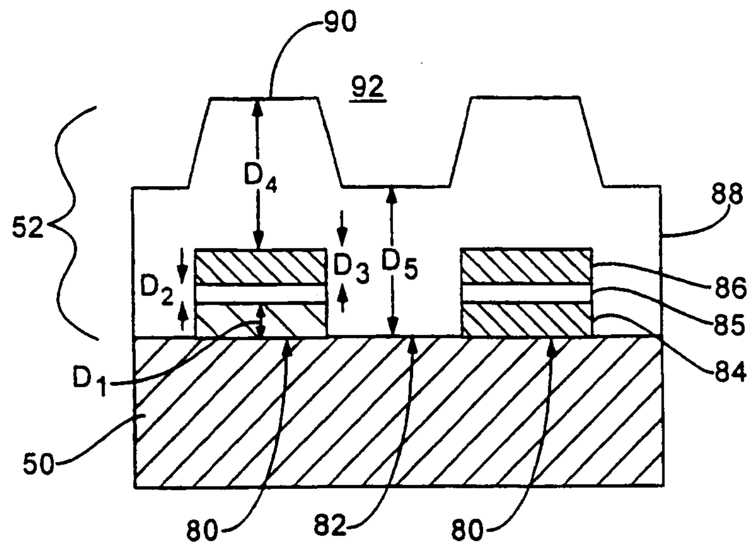
90
92
52
D4
D3
D5
D2
D1
88
86
85
84
50
80
82
80

FIG. 4A

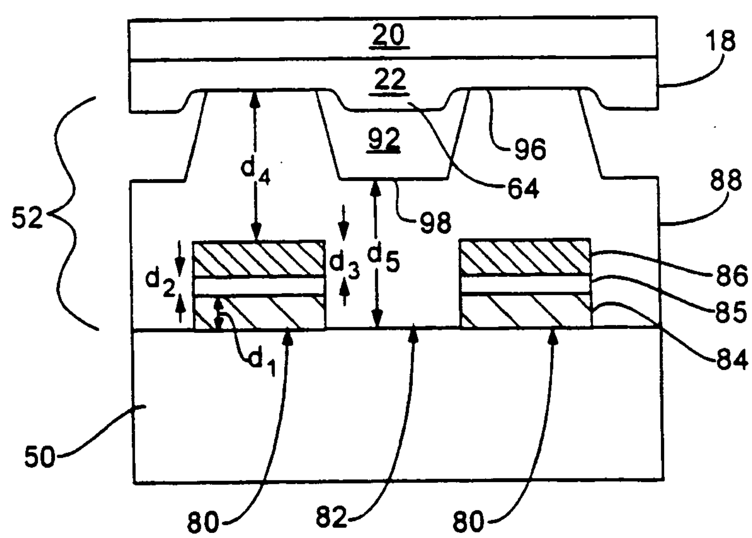
20
18
22
92
96
64
52
d4
98
88
d3
d5
d2
d1
86
85
84
50
80
82
80

FIG. 4B

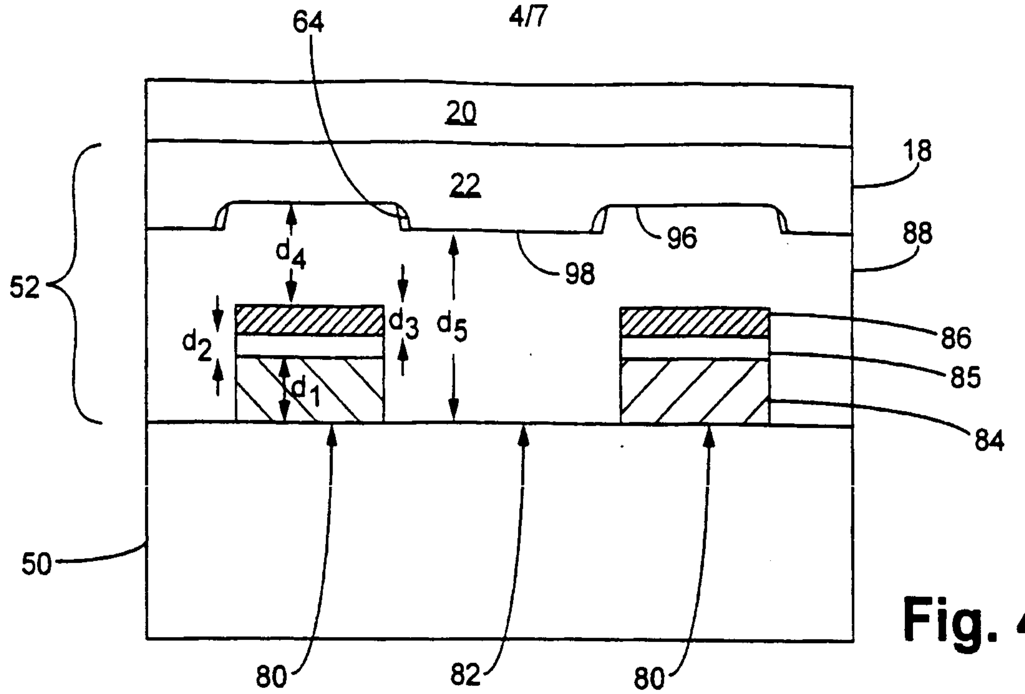

Fig. 4C

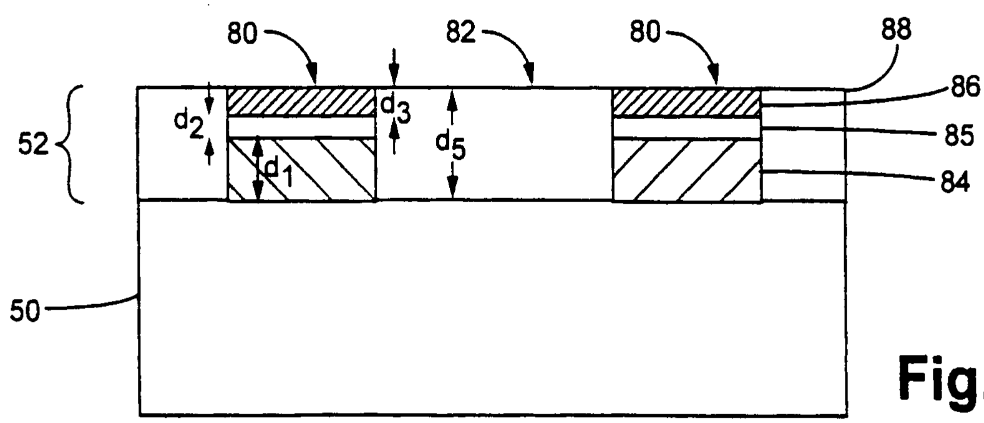

Fig. 4D

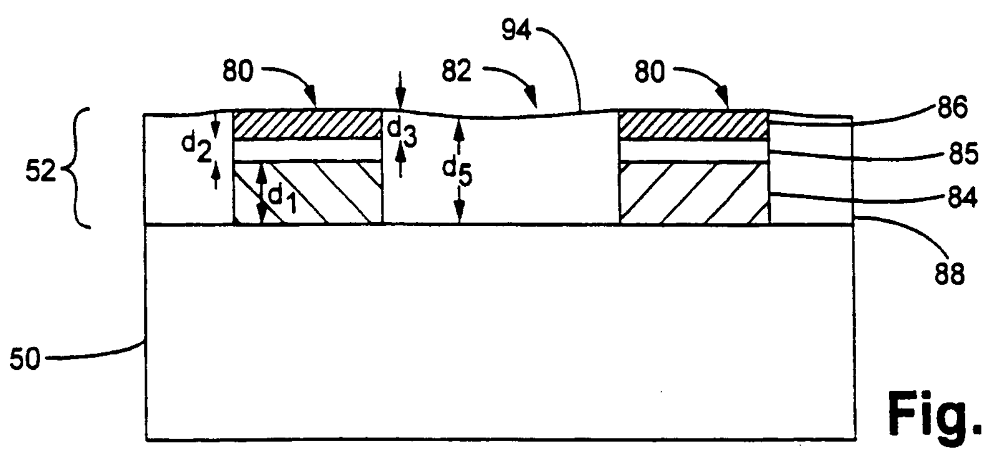

Fig. 4E

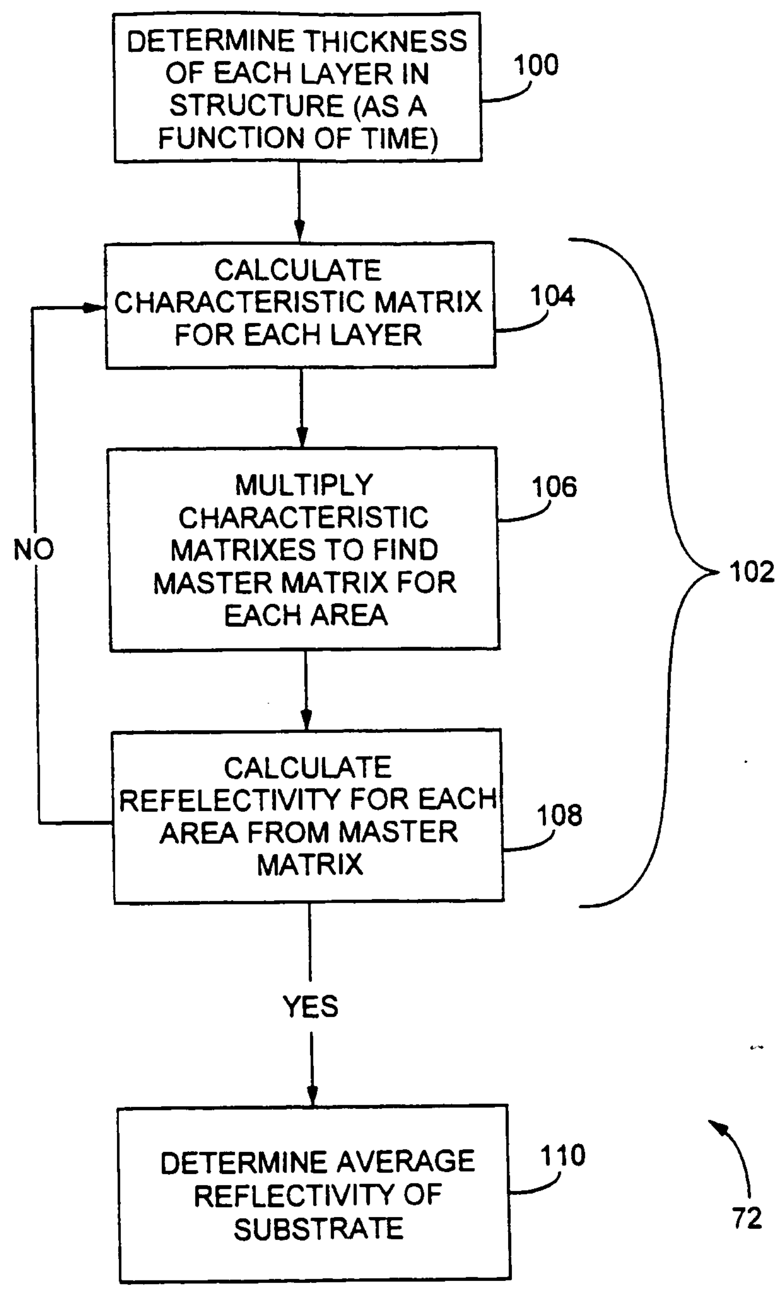
DETERMINE THICKNESS OF EACH LAYER IN STRUCTURE (AS A FUNCTION OF TIME)
100
CALCULATE CHARACTERISTIC MATRIX FOR EACH LAYER
104
MULTIPLY CHARACTERISTIC MATRIXES TO FIND MASTER MATRIX FOR EACH AREA
106
NO
102
CALCULATE REFELECTIVITY FOR EACH AREA FROM MASTER MATRIX
108
YES
DETERMINE AVERAGE REFLECTIVITY OF SUBSTRATE
110
72

Fig. 5

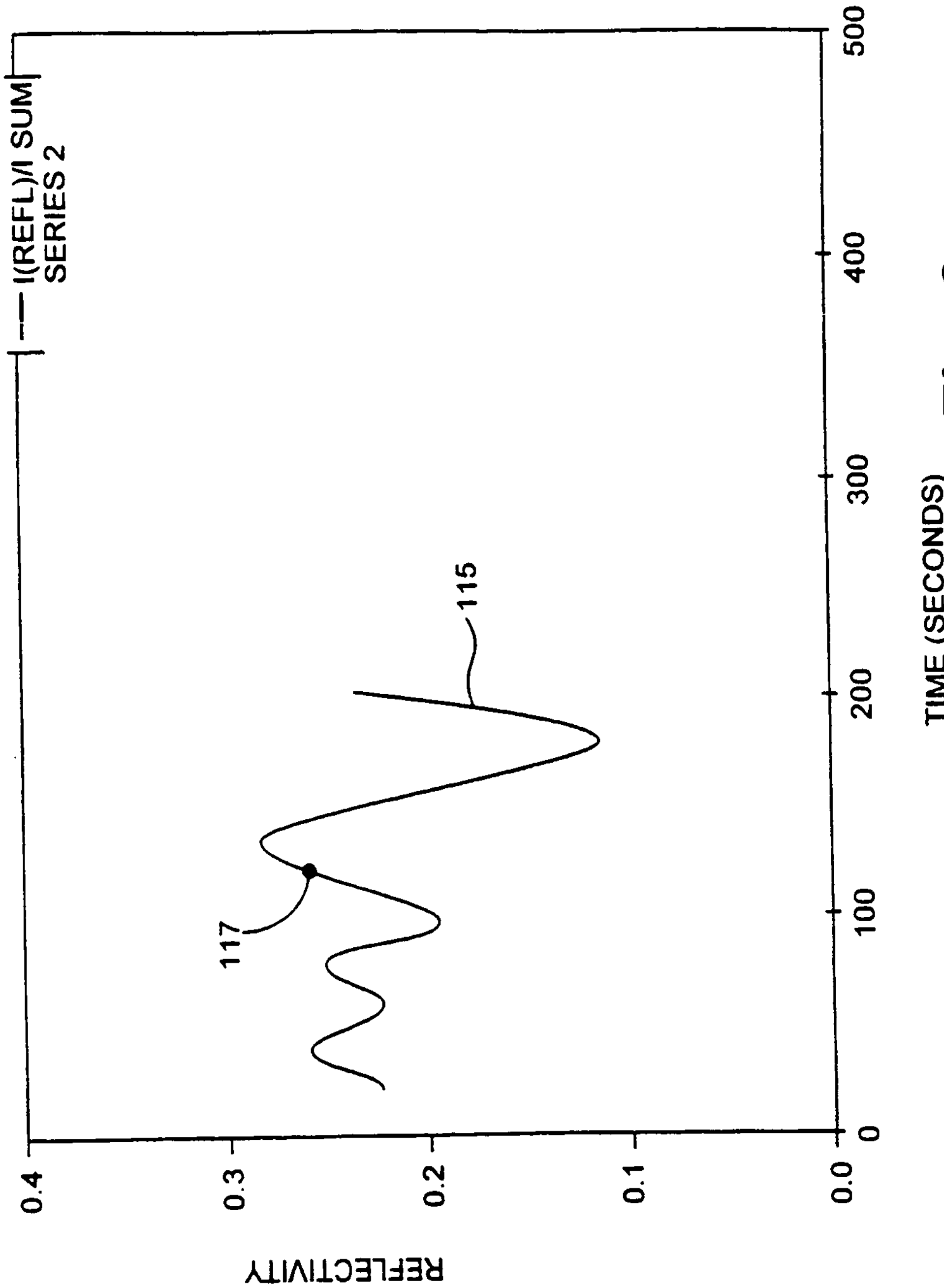
I(REFL)/I SUM
SERIES 2
REFLECTIVITY
0.4
0.3
0.2
0.1
0.0
0
100
200
300
400
500
TIME (SECONDS)
115
117

Fig. 6

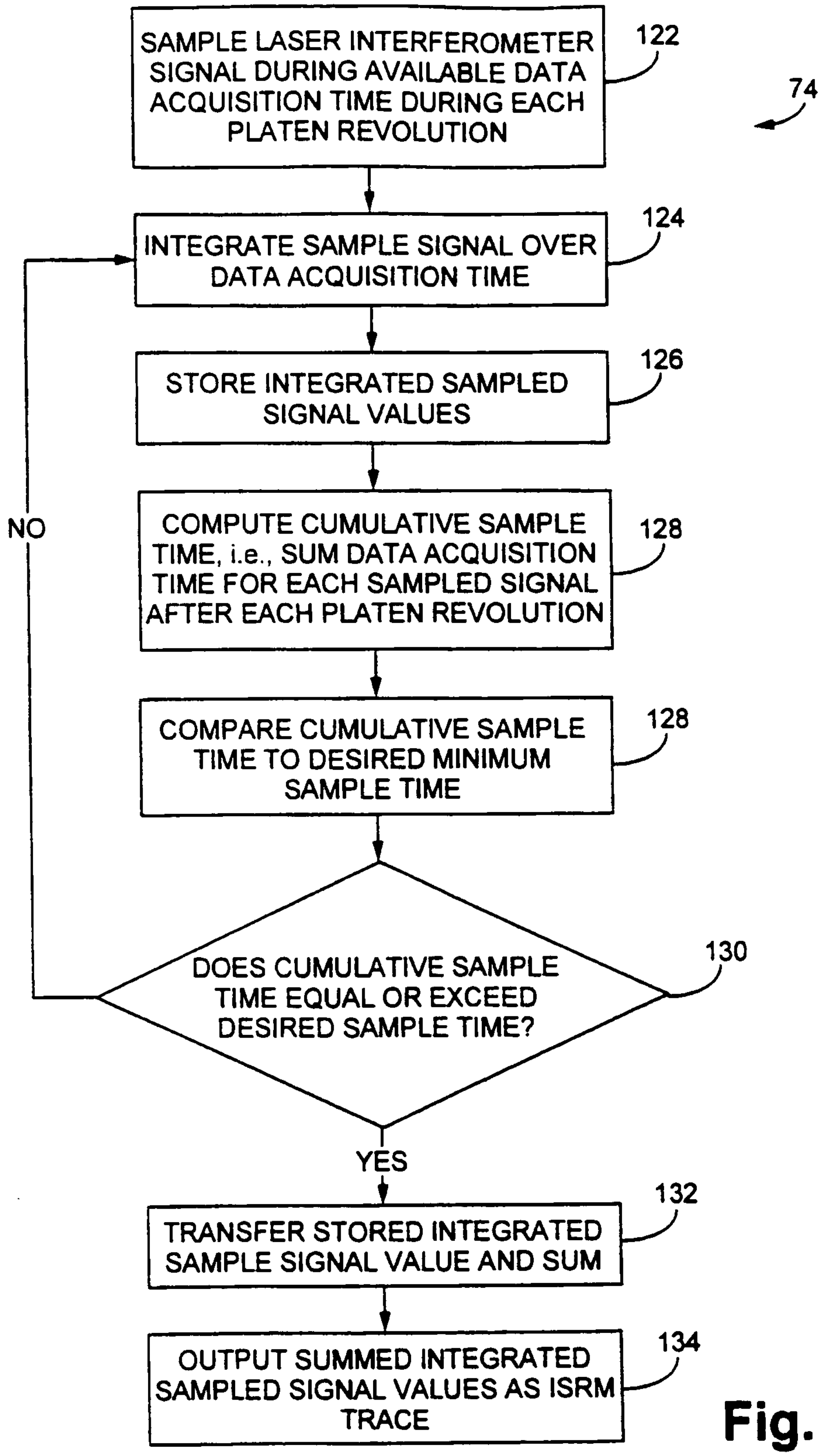
SAMPLE LASER INTERFEROMETER SIGNAL DURING AVAILABLE DATA ACQUISITION TIME DURING EACH PLATEN REVOLUTION
122
74
INTEGRATE SAMPLE SIGNAL OVER DATA ACQUISITION TIME
124
STORE INTEGRATED SAMPLED SIGNAL VALUES
126
NO
COMPUTE CUMULATIVE SAMPLE TIME, i.e., SUM DATA ACQUISITION TIME FOR EACH SAMPLED SIGNAL AFTER EACH PLATEN REVOLUTION
128
COMPARE CUMULATIVE SAMPLE TIME TO DESIRED MINIMUM SAMPLE TIME
128
DOES CUMULATIVE SAMPLE TIME EQUAL OR EXCEED DESIRED SAMPLE TIME?
130
YES
TRANSFER STORED INTEGRATED SAMPLE SIGNAL VALUE AND SUM
132
OUTPUT SUMMED INTEGRATED SAMPLED SIGNAL VALUES AS ISRM TRACE
134

Fig. 7

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 98/16902

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G01B11/06 H01L21/66

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H01L G01B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 768 512 A (LUCENT TECHNOLOGIES INC) 16 April 1997 see page 3, line 48 - page 4, line 20 see page 4, line 54 - page 5, line 5 see page 5, line 6 - page 6, line 6 see page 6, line 48 - page 7, line 17 see page 8, line 41 - page 9, line 7	1-13
Y		14-17

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
20 October 1998	02/11/1998

Name and mailing address of the ISA	Authorized officer
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INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 98/16902

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
Y	EP 0 738 561 A (APPLIED MATERIALS INC) 23 October 1996 see abstract see column 1, line 3 - line 6 see column 1, line 39 - column 7, line 31	14-17
A	see column 6, line 37 - line 40 see column 11, line 50 - column 12, line 4 see column 15, line 3 - line 27 see figure 2	1-13
A	E. HECHT: "Optics" 1987 , ADDISON-WESLEY , READING, MA, USA XP002081345 see page 373 - page 375	2,3,5, 13,14
A	US 5 290 396 A (SCHOENBORN PHILIPPE ET AL) 1 March 1994 see column 3, line 20 - column 5, line 58 see column 7, line 10 - column 9, line 22 see figure 8	7-9
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3

I. national Application No
PCT/US 98/16902

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		JP 7235520 A	05-09-1995